The charm and beauty of probing CP violation with the CMS detector

Alberto Bragagnolo (University & INFN PD), on behalf of the CMS Collaboration

CERN LPCC EP-LHC Seminar Series
16 April 2024
Introduction
Why we need CP violation?

- **Baryon asymmetry remains one of the great mysteries of modern physics**
- Half a century ago, Andrei Sakharov proposed three necessary **conditions** for a baryon-generating process:
  1. Baryon number violation
  2. C and **CP violation (CPV)**
  3. Non thermal equilibrium
- In the Standard Model (SM) CP is **conserved** by the strong and electromagnetic interactions, but it is **violated** by the weak force
  - CPV was first observed in 1964 by Fitch and Cronin using neutral kaons
  - P violation was proposed by Lee and Yang (1956) and experimentally observed by Wu (1957)
- **CPV** is allowed in the SM, but the amount is **insufficient** to account for the observed baryon asymmetry of the universe
  - Sources of CPV beyond the SM have to exist
  - CPV observables are often precisely predicted and very sensitive to new physics
CP violation in the SM

- In the SM quark transitions are possible through flavor-changing weak interactions
- Information about the strength of the transition is contained in the Cabibbo-Kobayashi-Maskawa (CKM) matrix
  - Parameters: 3 angles + 1 complex phase
- The single complex phase allows for CP violation
- In the SM, the CKM matrix is unitary
  - Unitary conditions can be represented by “unitary triangles”

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- E.g.: $u \rightarrow b$ amplitude
  - $|V_{ub}| \exp(-i\delta_{CP})$
- E.g.: $\bar{u} \rightarrow \bar{b}$ amplitude
  - $|V_{ub}| \exp(i\delta_{CP})$
Interlude: flavor mixing

- Neutral K, D, and B mesons are subject to **flavor mixing**, that is oscillations between their C-conjugate states before decay
- They propagate as light and heavy mass eigenstates which are described by a superposition of flavor states:
  \[
  |M^0_{L,H}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad (|q|^2 + |p|^2 = 1)
  \]
- The system is characterized by the parameters
  \[
  m \equiv \frac{m_H + m_L}{2} \quad \Gamma \equiv \frac{\Gamma_H + \Gamma_L}{2}
  \]
  \[
  \Delta m \equiv m_H - m_L \quad \Delta \Gamma \equiv \Gamma_L - \Gamma_H
  \]
  - The flavor eigenstates oscillate with period \( T = 2\pi/\Delta m \)
- **CPV in mixing**, i.e. \( Pr(M^0 \rightarrow \overline{M}^0) \neq Pr(\overline{M}^0 \rightarrow M^0) \), implies \(|q/p| \neq 1\)

Ref: LHCb Collab. *Nat.Phys.18*(2022)1-5
Types of CP violation

- Observable CP violation in weak interaction can be classified into three different types
  1. **Direct** CPV in **decays**
     ○ Observed in K, B, and D mesons
  2. **Indirect** CPV in **mixing**
     ○ Observed in $K^0$ oscillations
  3. CPV in decay/mixing **interference**
     ○ Observed in $K^0$, $B^0$ and $B_s$ mesons

- Defining $A_f$ the $M \rightarrow f$ amplitude, the CPV information can be coded in the **rephasing invariant** complex parameter $\lambda$

\[
\lambda \equiv \frac{q A_f}{p A_f} \left\{ \begin{array}{ll}
|q/p| \neq 1 & \rightarrow \text{direct CPV} \\
|\lambda| = 1, \text{Im}(\lambda) \neq 0 & \rightarrow \text{interference CPV}
\end{array} \right.
\]
The CMS detector

CMS is a general purpose detector able to perform a vast range of physics studies, including flavor physics

- **Excellent tracking system** able to reconstruct vertices with high decay time resolution (e.g., $\sigma_t \sim 65$ fs for $B_s \rightarrow J/\psi \phi$) up to $|\eta| < 2.5$
  - Complementary to LHCb ($2 < |\eta| < 5$)
- **Enormous amount of data collected**
  - ~ $7.5 \cdot 10^{13}$ bb pairs produced at Point 5 during Run 2 (geometric acceptance not considered)
  - High pile up $N_{PV} \sim 40$ (in Run 2)
  - No reliable hadronic particle identification available

Some CMS flavor physics highlights from recent years
- $B_s \rightarrow \mu^+\mu^-$ (world’s most precise) [PLB842(2023)137955]
- $\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$ observation [PRL131(2018)091903]
- $f_s/f_u$ measurements [PRL131(2023)121901]
- Triple $J/\psi$ production observation [Nat.Phys.19(2023)338]
- R(K) LFU test [BPH-22-005]
- R(J/ψ) LFU test [BPH-22-012]
Search for CP violation in $D^0 \rightarrow K_S K_S$

CMS PAS BPH-23-005

Dataset: 2018 B Parking (41 fb$^{-1}$)
Motivations

- **CP violation in the up-quark sector is not studied as well as in the down-quark one**
  - Expected to be suppressed by the GIM mechanism and CKM element size

- **Observation of a significant CPV ★ hints of BSM physics**
  - First observation of CPV in D mesons in 2019 by LHCb with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays [PRL122(2019)211803]

- **This seminar presents a measurement of the direct CPV in $D^0 \to K_S K_S$ decays**
  
  $$A_{CP} = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}$$

- From theory, CPV in $D^0 \to K_S K_S$ could be as large as $O(1\%)$ [PRD92(2015)054036]
The CMS B parking dataset

- Designed to allow CMS to perform B physics measurements on difficult/impossible to trigger final states (e.g. fully hadronic final states)
- Achieved with a set of single muon triggers (tags) with different thresholds in $p_T$ and impact parameter
  - Luminosity decreases during a run ➜ less restrictive triggers enabled
    - Maximises the available trigger bandwidth
  - Events are parked for later reconstruction
  - Very high purity of ~80%
- No impact on the standard CMS physics programme
- 10 billion unbiased B hadron decays collected in 2018 ($L_{\text{int}} \sim 41 \text{ fb}^{-1}$)

References
- [CMS-EXO-23-007]
- [CMS-BPH-22-005]
Measurement strategy

- **Use** $D^0$ from $D^{*+} \rightarrow D^0 \pi^+$ and $D^{*-} \rightarrow \bar{D}^0 \pi^-$, so that the pion charge tags the $D^0$ flavor
- **This introduces** the $D^{*+}/D^{*-}$ differences in the measurement

\[
A_{raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)}
\]

\[
A_{prod} = \frac{\sigma_{pp \rightarrow D^{*+}X} - \sigma_{pp \rightarrow D^{*-}X}}{\sigma_{pp \rightarrow D^{*+}X} + \sigma_{pp \rightarrow D^{*-}X}}
\]

\[
A_{det} \approx \frac{\epsilon_{\pi^+} - \epsilon_{\pi^-}}{\epsilon_{\pi^+} + \epsilon_{\pi^-}}
\]

- **Strategy**: measure $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K_S K_S) - A_{CP}(D^0 \rightarrow K_S \pi^+ \pi^-)$
  - Reference channel is very similar in kinematics and topology $\Rightarrow A_{prod}$ and $A_{det}$ cancel out
  - CPV in $D^0 \rightarrow K_S \pi^+ \pi^-$ already measured consistent with zero [PRD86(2012)032007]

\[
\Delta A_{CP} = A_{raw}(D^0 \rightarrow K_S K_S) - A_{raw}(D^0 \rightarrow K_S \pi^+ \pi^-)
\]
Event selection

- **First**, $K_s \rightarrow \pi^+\pi^-$ are reconstructed fitting the $\pi$ tracks to a common vertex
  ○ $|m(\pi^+\pi^-) - m(K_s^{\text{w.a.}})| < 20$ MeV, $p_T(K_s) > 2.2(1.0)$ GeV
- In the **signal channel**, two $K_s$ candidates are required and fitted to a common vertex to form $D^0 \rightarrow K_sK_s$ candidates
  ○ $1.7$ GeV < $m(K_sK_s)$ < $2.0$ GeV
  ○ $K_s$ displacement in $xyz$ from the $D^0$ vertex >9σ and >7σ
  ○ $D^0$ displacement in $xyz$ (xy) from the PV >9σ (>2σ)
- In the **reference channel**, two track with $p_T > 0.6$ GeV are used to form the $D^0 \rightarrow K_s\pi^+\pi^-$ candidate
  ○ $1.823 < m(K_s\pi^+\pi^-) < 1.908$ GeV
- **Finally**, an additional track with -1.2 < $|\eta|$ < 1.2 and $p_T > 0.36$ GeV is added to form $D^{*+} \rightarrow D^0\pi^+$ candidates
  ○ $m(D^0\pi^+) = m(D^0\pi^+) - m(D^0) + m_{\text{PDG}}(D^0)$

- **Background suppression**: several fits corresponding to incorrect topologies are performed and vertex probabilities requirements are imposed
**$A_{CP}$ extraction**

To extract the CP asymmetry a **2D maximum-likelihood fit** is performed on the invariant mass of the $D^{**}$ and $D^{0}$ invariant mass

- Simultaneous on the $D^{**}$ and $D^{*}$ samples with only the yields left to float
- **Main fit components** (signal channel):
  - $D^{0} \times D^{**}$, the signal component
  - $D^{0} \times bkg$, real $D^{0}$ and background pion
  - $bkg \times bkg$, background in both dimensions
- **Signal pdf**: 2 x Johnson’s SU
- **Background pdf**: polynomials, exponentials, threshold function
- **Yields:**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion charge</td>
<td>N</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>944 800 ± 3 500</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>930 150 ± 3 400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pion charge</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>1095 ± 46</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>951 ± 44</td>
</tr>
</tbody>
</table>

**Systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(D\pi^\pm)$ signal model</td>
<td>0.10</td>
</tr>
<tr>
<td>$m(D\pi^\pm)$ background model</td>
<td>0.02</td>
</tr>
<tr>
<td>$m(K_S^0 K_S^0)$ signal model</td>
<td>0.04</td>
</tr>
<tr>
<td>$m(K_S^0 K_S^0)$ background model</td>
<td>0.02</td>
</tr>
<tr>
<td>$m(K_S^0 K_S^0)$ fit range</td>
<td>0.04</td>
</tr>
<tr>
<td>Reweighting</td>
<td>0.09</td>
</tr>
<tr>
<td>$\Delta A_{CP}$ in MC</td>
<td>0.13</td>
</tr>
<tr>
<td>Total</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Results and outlook

- Putting everything together, $\Delta A_{CP}$ is measured

$$\Delta A_{CP} = 6.3 \pm 3.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \%$$

- Using the world-average value of $A_{CP}(K_S \pi^+\pi^-) = (-0.1 \pm 0.8)\%$, $A_{CP}(K_S K_S)$ is found to be

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = 6.2 \pm 3.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.8(A_{CP}(K_S^0 \pi^+\pi^-)) \%$$

- Consistent with no CP violation at 2$\sigma$, with LHCb $[\text{PRD104}(2021)L031102] \ ((-3.1 \pm 1.3)\%)$ at 2.7$\sigma$ and Belle $[\text{PRL119}(2017)171801] \ [(0.0 \pm 1.5)\%]$ at 1.8$\sigma$

- This is the first CMS study of CP violation in the charm sector, paving the way for future measurements
  - More data
  - Refined techniques
  - Different channels
Measurement of the $B_s \rightarrow J/\psi \, K_S$ effective lifetime

CMS PAS BPH-22-001
Motivations

- $B_s$ mesons are produced in flavor eigenstates, but propagate as mass ones, which, if no CPV in the mixing, coincide with CP eigenstates

$$B_s^H \rightarrow \text{CP odd} \quad B_s^L \rightarrow \text{CP even}$$

- These can have different lifetimes (as for the $B_s$), allowing the probe of the mass eigenstate rate asymmetry $A_{\Delta \Gamma}$, directly related to the CPV observable $\lambda$

$$A_{\Delta \Gamma} = \frac{R_H - R_L}{R_H + R_L} = \frac{-2 R(\lambda)}{1 + |\lambda|^2}$$

  - $R_H$ and $R_L$ are related to the untagged decay rate as

$$\Gamma(B_s \rightarrow f) + \Gamma(\bar{B}_s \rightarrow f) = R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t}$$

- This seminar presents a measure of the $B_s$ effective lifetime $\tau$ in the CP-odd final state $J/\psi K_S$ performed with the CMS Run 2 data set

- This process is related to $B^0 \rightarrow J/\psi K_S$ via U-spin flavor symmetry
  - $A_{\Delta \Gamma}$ can be used to determine penguin contributions to the measurement of $\sin(2\beta)$
  - The CKM angle $\gamma$ can also be probed in $B_s \rightarrow J/\psi K_S$
The effective lifetime

- The effective lifetime is defined as the expected value of the untagged decay rate

\[
\tau(J/\psi K_S) \equiv \frac{\int_0^\infty t(\Gamma_{B_s \rightarrow J/\psi K_S} + \Gamma_{\bar{B}_s \rightarrow J/\psi K_S})dt}{\int_0^\infty (\Gamma_{B_s \rightarrow J/\psi K_S} + \Gamma_{\bar{B}_s \rightarrow J/\psi K_S})dt} = \frac{\tau_{B_s}}{1 - y_s^2} \left(1 + 2A_{\Delta \Gamma}y_s + y_s^2\right) \left(1 + A_{\Delta \Gamma}y_s\right)
\]

- Using the latest measurements and assuming the SM \((A_{\Delta \Gamma} = 0.94 \pm 0.07, \tau_{B_s} = 1.520 \pm 0.005 \text{ ps}, \Delta \Gamma = 0.084 \pm 0.005 \text{ ps}^{-1})\)

\[
\tau(J/\psi K_S)_{SM} = 1.62 \pm 0.02 \text{ ps}
\]

  ○ Available measurement from LHCb: \(\tau(J/\psi K_S) = 1.75 \pm 0.14 \text{ ps}\) [Nucl.Phys.B(2013)873]

- In this analysis the decay time is measured in the transverse plane as

\[
t = \frac{L_{xy} \cdot M_{B_s}}{p_T}
\]
Event selection and efficiency

- **Trigger**: $J/\psi \rightarrow \mu^+\mu^-$ candidate with $p_T > 20$ (25) GeV for 2016 (2017-18)
- **Offline $K_S \rightarrow \pi^+\pi^-$ selection**
  - Displaced by $>15\sigma$ from the beamspot and $>5\sigma$ from the $B_s$ vertex
  - Invariant mass within 70 MeV from world-average value
- **Background sources**
  - $\Lambda \rightarrow p\pi^-$: suppressed with constraints on the decay kinematics
  - $B^0 \rightarrow J/\psi K_S$: irreducible, treated as a control channel
  - $B^0 \rightarrow J/\psi K^{*0}$: negligible
  - Combinatorial: suppressed with dedicated BDT selection
- **Time efficiency**
  - Measured in simulations for $B_s$ and $B^0$ (control channel)
    \[ \epsilon(t) = \frac{t_{\text{reco}}}{t_{\text{gen}} \otimes \delta(t)} \]
  - Modeled with a combination of polynomials and logistic functions
Fit and results

- The effective lifetime is measured with a 2D UML fit to the invariant mass and proper decay time
  - The decay time uncertainty is used as a conditional parameter
  - Both the effective lifetimes of the signal $B_s$ and control channel $B^0$ are fitted
  - The control channel is used to validate most of the measurement components
- Results (using $727 \pm 35$ $B_s$ signal candidates)
  - $\tau(J/\psi K_S)^{\text{eff}} = 1.59 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)}$ ps
    - The control channel’s effective lifetime is found to be in good agreement with the world-average value
- The measured $B_s \rightarrow J/\psi K_S$ effective lifetime is in agreement with the SM prediction and compatible with the previous LHCb results at $2.1\sigma$
- This is the most precise measurement of this quantity to date
Measurement of the time-dependent CP violation in $B_s$ mesons

CMS PAS BPH-23-004

Dataset: 2017-18 (96 fb$^{-1}$)
Motivations

- **Bₙ mesons decays** allow us to study the time-dependent CP violation generated by the interference between direct decays and flavor mixing
  - CPV in the interference is possible even if there is no CPV in decay and mixing
- **The weak phase φₛ** is the main CPV observable
  - Predicted by the SM to be φₛ ≈ -2βₛ (βₛ → angle of the Bₛ unit. triangle)
    - Neglecting contributions from higher-order diagrams (Δφₛ loop ≈ 3±10 mrad)
  - βₛ determined by CKM global fits to be -2βₛ = -37 ± 1 mrad [CKMfitter, UTfit]
- **New physics** can change the value of φₛ up to ~100% via new particles contributing to the flavor oscillations [RMP88(2016)045002]

- **This seminar** presents the latest CMS results with the golden channel Bₛ → J/ψ φ(1020) → μ⁺μ⁻K⁺K⁻
A long history: flagship CPV analysis at LHC

- $\phi_s$ has been first measured by the Tevatron experiments D0 and CDF
- At LHC $\phi_s$ has been measured several times by ATLAS, LHCb, and CMS
  - LHCb has measured $\phi_s$ in several other channels, such as $B_s \rightarrow J/\psi \pi^+\pi^-$, $B_s \rightarrow J/\psi(e^+e^-)K^+K^-$, $B_s \rightarrow \psi K^+K^-$, $B_s \rightarrow D_s^+D_s^-$, ...
- Preliminary world-average (before this work): $\phi_s^{J/\psi KK} = -50 \pm 17$ mrad (Jevtic Li, CERN Seminar 2023)

From: [Jevtic Li, CERN seminar (2023)]
A time-, flavor- and angular-dependent measurement

Core ingredients

- **Time-dependent angular analysis** to separate the CP eigenstates (“transversity basis” used)
- **Time-dependent flavor analysis** to resolve the $B_s$ mixing oscillations ($T \sim 350$ fs)

\[
a_{CP}(t) = \frac{-\eta_{fs} \sin(\phi_s) \sin(\Delta m_s t)}{\cosh(\frac{1}{2} \Delta \Gamma_s t) - \eta_{fs} \cos(\phi_s) \sinh(\frac{1}{2} \Delta \Gamma_s t)}
\]

- CP violation
- Flavor oscillations

Transversity basis

Decay rate for a CP-even final state

sensitivity $\propto \sqrt{\frac{\epsilon_{tag} \mathcal{P}_{tag}^2 N_{\text{sig}}}{2}} \sqrt{\frac{N_{\text{sig}}}{N_{\text{sig}} + N_{\text{bkg}}}} e^{-\frac{\Delta m_s^2}{2}}$
Decay rate model

\[ d^4\Gamma(B_s) \frac{d\Theta}{dt} \propto \sum_{i=1}^{10} O_i(t, \alpha) g_i(\Theta) \]

\[ O_i(t, \alpha) = N_i e^{-i\Delta s t} \left[ a_i \cosh \left( \frac{\Delta s t}{2} \right) + b_i \sinh \left( \frac{\Delta s t}{2} \right) + c_i (1 - 2\omega) \cos (\Delta m s t) + d_i (1 - 2\omega) \sin (\Delta m s t) \right] \]

- **Conventions**
  - \([A_\parallel] = |A_0|^2 - |A_\perp|^2\)
  - \(\delta_0 = 0\)
  - \(\delta_{S\perp} = \delta_s - \delta_\perp\)
  - \(\Delta\Gamma_s > 0\)

- **Physics parameters**
  - \(\phi_s, |\lambda|\)
  - \(\Delta\Gamma_s, \Gamma_s, \Delta m_s\)
  - \(|A_0|^2, |A_\perp|^2, |A_S|^2\)
  - \(\delta_\parallel, \delta_\perp, \delta_{S\perp}\)

- **S-P wave effective coupling**
  - \(k_{SP} \approx 0.54\)
  - Introduced since \(m(K^+K^-)\) is not fitted
  - Evaluated from the S- and P-wave lineshape interference

- **Flavor tag decision** (flips \(c_i\) and \(d_i\) signs)

- **Mistag probability**

- **Angular variables**

- **Decay time**

- **Most sensitive terms for SM \(\phi_s\)**

---

Alberto Bragagnolo

CP violation at CMS

24/44
Trigger strategy

Muon-tagging trigger

- $J/\psi \rightarrow \mu^+\mu^-$ candidate plus an additional muon (for tagging)
- $\approx 50,000$ signal candidates
- Used for time resolution modeling
- Tagging algorithms deployed: OS-muon
  - $P_{\text{tag}} \sim 10\%$ (muon at trigger level enhance tagging efficiency)

Standard trigger

- Displaced $J/\psi \rightarrow \mu^+\mu^-$ candidate + $\phi(1020) \rightarrow K^+K^-$
- $\approx 450,000$ signal candidates
- Tagging algorithms deployed: OS-muon, OS-electron, OS-jet, Same Side
  - $P_{\text{tag}} \sim 5\%$
Dataset and selection

- **Dataset**: $L_{\text{int}} = 96 \, \text{fb}^{-1}$ collected in 2017-2018
  - Why no 2016 data? Very different data set (old inner tracker detector with worse time resolution and different trigger menu)
- **Signal candidates**: $491 \pm 270 \pm 950$
- Notable selection requirements:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_t$ (muon-tagging HLT)</td>
<td>$&gt; 60 , \mu\text{m}$</td>
</tr>
<tr>
<td>$c_t$ (standard HLT)</td>
<td>$&gt; 100 , \mu\text{m}$</td>
</tr>
<tr>
<td>$c_t/\sigma_{c_t}$ (standard HLT)</td>
<td>$&gt; 3$</td>
</tr>
<tr>
<td>$</td>
<td>m(K^+K^-) - m_{\phi(1020)}</td>
</tr>
<tr>
<td>$</td>
<td>m(\mu^+\mu^-) - m_{\psi}</td>
</tr>
</tbody>
</table>

- To avoid overlaps, events that pass both trigger category selections are placed only in the muon-tagging one
  - This depletes the standard trigger category of OS muons
- The PV of choice is the closest in 3D to the line that passes through the SV and parallel to the $B_s$ momentum
Decay time and its resolution

- The time dependence of the decay rate is parametrized with the proper decay length $c t$, measured in the transverse plane as:

$$c t = c \cdot \frac{m_{B_{s}}^{w.a.} \cdot L_{xy}}{p_{T}} \quad \text{with} \quad L_{xy} = ||\bar{r}_{xy}(SV) - \bar{r}_{xy}(PV)||$$

- Its uncertainty is obtained by fully propagating the uncertainties in $L_{xy}$ and $p_{T}$
  - The uncertainty on $L_{xy}$ dominates for most of the $c t$ spectrum, with $\sigma(p_{T})$ taking over at high values ($c t \gtrsim 3 \text{ mm}$)

- The $c t$ uncertainty is calibrated in a prompt data sample of $B_{s} \rightarrow J/\psi \phi$, obtained by removing the displacement requirement in the muon-tagging data sets
  - Modeled with two gaussians to obtain the effective dilution and resolution

$$\delta_{eff} = \sqrt{-2 \ln D} \quad \text{with} \quad D = \sum_{i=1}^{2} f_{i} \exp \left( -\frac{\sigma_{i} \Delta m_{s}^{2}}{2} \right)$$

- Excellent agreement found, with corrections $\sim 5\%$
Acceptance and efficiency effects

- The efficiency in selecting and reconstructing the $B_s$ candidates is **not** independent of the decay time and angular observables
  - To properly fit the decay rate model an efficiency parametrization is needed

**Time efficiency**

- Modeled in the $B^0 \rightarrow J/\psi K^{*0}$ data control channel with corrections from simulations
- Ultimately parametrized with Bernstein’s polynomials

\[
\varepsilon_{B^0}^{\text{data}}(ct) = \frac{N_{B^0}(ct)}{e^{-\tau_{B^0}} \otimes P_{B^0}(\sigma_{ct})}
\]

\[
\varepsilon_{B_s}^{\text{data}}(ct) = \varepsilon_{B^0}^{\text{data}}(ct) \cdot \frac{\varepsilon_{B_s}^{\text{MC}}(ct)}{\varepsilon_{B^0}^{\text{MC}}(ct)}
\]

**Angular efficiency**

- Estimated with KDE distributions in simulated events
- The simulated data samples are corrected to match the data
  - An iterative procedure is used to simultaneously correct the kinematics of the final state particles and the differences in the physics parameters set in the MC with respect to what measured in the data
Flavor tagging overview

- A cutting-edge flavor tagging framework has been engineered to extract the best possible results from data.
- Four DNN-based algorithms are used, divided into two main categories:
  - Same side (SS): exploits the $B_s$ fragmentation
    1. SS tagger: leverages charge asymmetries in the $B_s$ fragmentation
  - Opposite side (OS): exploits decay products of the other B hadron in the event
    2. OS muon: leverages $b \rightarrow \mu^+X$ decays
    3. OS electron: leverages $b \rightarrow e^+X$ decays
    4. OS jet: capitalizes on charge asymmetries in the OS $b$-jet
- Only the OS-muon tagger is applied in the muon-tagging trigger category.
  - The OS-electron, OS-jet and SS are applied only to the standard trigger category.
Flavor, neural networks, and probabilities

- The **tagging inference logic** differs between algorithms
  - **Lepton taggers** (OS muon, OS electron)
    - Lepton charge $\rightarrow \xi_{\text{tag}}$; DNN score $\rightarrow \omega_{\text{tag}}$  
      $\begin{align*}
      \text{OS } \ell^- \rightarrow \text{OS } b_{\text{tag}} \rightarrow \text{signal } B_s \\
      \text{OS } \ell^+ \rightarrow \text{OS } \bar{b}_{\text{tag}} \rightarrow \text{signal } \bar{B}_s \\
      \omega_{\text{tag}} = 1 - S_{\text{DNN}}
      \end{align*}$

  - **Charge-based taggers** (OS jet, SS)
    - DNN score $\rightarrow \text{Prob}(B_s) \rightarrow \xi_{\text{tag}}, \omega_{\text{tag}}$  
      $\begin{align*}
      S_{\text{DNN}} > 0.5 + \epsilon_{\text{tag}} \rightarrow \text{signal } B_s \quad \text{with } \quad \omega_{\text{tag}} = 1 - S_{\text{DNN}} \\
      S_{\text{DNN}} < 0.5 - \epsilon_{\text{tag}} \rightarrow \text{signal } \bar{B}_s \quad \text{with } \quad \omega_{\text{tag}} = S_{\text{DNN}}
      \end{align*}$

- $\epsilon$ is used to remove events with $\omega_{\text{tag}} \sim 50$

- The algorithms are optimized and trained in simulated events and calibrated in data with self-tagging $B^+ \rightarrow J/\psi K^+$ decays
  - The calibration is performed by comparing $\omega_{\text{tag}}$ predicted by the DNN and the one measured in data
Calibration strategy (and other tricks)

- A multi-pronged strategy has been devised to improve the $\omega_{\text{tag}}$ estimation and suppress systematic effects
  1. All models are constructed from the start as probability estimators, i.e. $\text{score} \sim \omega_{\text{tag}}$
     - Loss function: cross-entropy, which is the likelihood for the probability $P(\text{true class} | \text{score})$
     - Output layer: Sigmoid function, which normalizes the output to a probability distribution
  2. All DNNs are calibrated with the Platt scaling, which ensures that the calibrated score is still a probability
     - The Platt scaling is a linear calibration of the score before the last sigmoid layer
  3. In calibrating the charge-based taggers (which provide a probability for $B_s$ vs $\bar{B}_s$):
     A. The output is symmetrized due to the initial LHC charge imbalance
        \[ s^{\text{sym}}_{\text{DNN}}(x) = \frac{s_{\text{DNN}}(x) + [1 - s_{\text{DNN}}(\overline{x})]}{2} \]
     B. The symmetry is explicitly forced in the calibration function by removing the constant term

This strategy cancels almost all the systematic effects associated with flavor tagging
OS-lepton tagging

- OS-lepton tagging techniques search for $b \rightarrow \ell \cdot X$ decays of the other $B$ hadron in the event
- The charge of the lepton is used as tagging feature and a fully connected DNN is used to estimate the mistag probability
- Lepton selection
  - Loose kinematic cuts
  - Separated from the signal $B$ meson
  - MVA discriminator against fakes
  - OS-electrons are searched only if no OS-muon is found in the event (explicit orthogonality)
- Mistag estimation
  - Fully connected DNN with ReLU activation and dropout
  - Inputs: lepton kinematics and surrounding activity
- Trained on simulated $B_s \rightarrow J/\psi \phi(1020)$ events and calibrated in $B^+ \rightarrow J/\psi K^+$ data

OS-Muon calibration (muon-tagging trigger 2018)

OS-Electron calibration (2018)
OS-jet tagging

- The OS-jet algorithm exploits charge asymmetries in the jet structure and is based on a DNN called DeepJetCharge
  - Inputs: features from signal B meson, OS jet and its constituents
    - NB: The only flavor asymmetry is in the charges
  - Based on the DeepSets architecture [ref]
- Jet selection
  - No OS-lepton candidate
  - At least 2 tracks with $|P_{z}| < 1$ cm
  - Separated from the signal B meson
  - Jet b-tagging discriminator
- Additional nearby tracks are used due to the poor jet clustering performance in the kinematic region of interest ($p_{T} < 20$ GeV)
- Trained on simulated $B_{s} \rightarrow J/\psi \phi$ events and calibrated in $B^{+} \rightarrow J/\psi K^{+}$ data
- The trained network produces the probability of signal B meson containing a $b$ quark (i.e. being a $B_{s}$)
- The score is finally used to compute both $\xi_{\text{tag}}$ and $\omega_{\text{tag}}$

\[
\begin{align*}
    s_{\text{DNN}} > 0.52 & \quad \text{tag} \quad \text{signal } B_{s} \quad \text{with} \quad \omega_{\text{tag}} = 1 - s_{\text{DNN}} \\
    s_{\text{DNN}} < 0.48 & \quad \text{tag} \quad \text{signal } \bar{B}_{s} \quad \text{with} \quad \omega_{\text{tag}} = s_{\text{DNN}}
\end{align*}
\]
SS tagger

- The SS tagger consists of a DNN (**DeepSSTagger**), derived from **DeepJetCharge**, able to probe the fragmentation products of a B meson and exploit tracks with high flavor correlation
- **DeepSSTagger** uses the kinematic information from up to 20 tracks (ordered by |IP_z|) around the reconstructed B meson
- Track selection
  - ΔR(trk, B) < 0.8, |IP_z(PV)| < 0.4 cm, |IP_xy(PV)|/σ_dxy < 1
  - Overlap with signal and OS is carefully avoided with geometrical cuts and vetos
- Trained on an equal-weight mixture of B_s → J/ψ φ and B^+ → J/ψ K^+ to make the model invariant for B_s ↔ B^+ for calibration purposes
  - Calibration directly in B_s was found to be not feasible in CMS
    - Tested: B_s → D_s^-π^+ (not enough stat.) and B_s^{**} → B^{+(s)}K^- (too much uncer. from B^{0**} bkg)
    - The trained network produces the probability of signal B meson containing a negatively charged quark alongside the b quark (i.e., being a B_s or B^+)
- Calibration
  - The SS is calibrated B^+ → J/ψ K^+ data, with residual differences ~10% corrected with simulations
  - Events with ω_{tag} > 0.46 are removed before the calibration and assumed untagged
Flavor tagging performance

- The SS and any one of the OS algorithms overlap in about 20% of the events
  - In these cases, the information is combined to improve the tagging inference

- **The combined flavor tagging framework achieves a tagging power of** $P_{\text{tag}} = 5.6\%$ **when applied to the $B_s$ data sample**
  - Among the highest ever recorded at LHC
  - $\times 3\sim 4$ improvement with respect to prev. CMS results

- **This is the first CMS implementation of the OS jet and same-side tagging techniques**
  - SS accounts for half of the performance

- Largest ever effective statistics $N_{B_s} \cdot P_{\text{tag}}$ ($490k \cdot 5.6\% \approx 27.5k$) for a single $\phi_s$ measurement

- The flavor tagging framework is validated in the $B^0 \rightarrow J/\psi K^{*0}$ data control channel with flavor mixing measurements, both integrated and time-dependent
Tagging validation with $B^0$ events

- The flavor tagging framework is validated in the $B^0 \rightarrow J/\psi K^{*0}$ control channel (~2M events)

- The time-dependent *mixing asymmetry* is measured to extract the flavor mixing oscillation frequency $\Delta m_d$ with a precision of ~1% (comparable with BaBar and Belle)
  - Excellent agreement with world-averages is observed
  - **No bias in mixing frequency measurements**

- Study performed also in each tagging category (see backup)

- The *time-integrated mixing* is also measured for each tagger and their dependency on the expected tagging dilution is compared
  - The dependency between the measured $A_{\text{mix}}$ and the estimated $D_{\text{tag}}$ is found to be well described by a linear relationship, indicating that all four techniques behave in the same predictable way
The physics parameters are extracted with **unbinned multidimensional extended maximum-likelihood (UML) fit** performed simultaneously on 12 data sets (2 trig. cat. x 2 years x 3 ξ_tag values)

- **Physics parameters**: \( \phi_s, |\lambda|, \Delta \Gamma_s, \Gamma_s, \Delta m_s, |A_0|^2, |A_\perp|^2, |A_S|^2, \delta //, \delta \perp, \delta_{S\perp} \)
- **Observables**: \( m_{Bs}, c_t, \sigma_{ct}, \cos \theta_T, \cos \psi_T, \phi_T, \omega_{tag} \)

**Fit model**

\[
P = f_{sig} P_{sig} + f_{bkg} P_{bkg} + f_{bkg} B^0 P_{bkg} B^0
\]

- The time efficiency is implemented as a *re-weighting* of the data events to drastically improve fit time
- The statistical uncertainties and fit bias are estimated with **1300 bootstrap distributions**
- The yield for the \( B^0 \rightarrow J/\psi K^{0*} \) is estimated directly in data with a 2D fit to the \( B_s \) invariant mass and its \( B^0 \) reflection
- The background from \( \Lambda_b \rightarrow J/\psi K^- p^+ \) is found to be negligible and is treated as a systematic uncertainty
Systematic uncertainty overview

- Model bias, flavor tagging, and angular efficiency are found to be the leading systematic sources for $\phi_s$
- The measurement is still heavily statistically limited for $\phi_s$
Validation: fit with individual tagging techniques

- To check the consistency and stability of the tagging framework, the fit to data is repeated with only one tagging algorithm deployed at a time
  - The grey area represents the result and statistical uncertainty of the full fit
  - Only flavor-sensitive parameters are presented
- Excellent agreement between the various tagging techniques
Results

### Fit results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit value</th>
<th>Stat. uncer.</th>
<th>Syst. uncer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ [mrad ]</td>
<td>$-73 \pm 23$</td>
<td>$\pm 7$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$ ]</td>
<td>$0.0761 \pm 0.0043$</td>
<td>$\pm 0.0019$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_s$ [ps$^{-1}$ ]</td>
<td>$0.6613 \pm 0.0015$</td>
<td>$\pm 0.0028$</td>
<td></td>
</tr>
<tr>
<td>$\Delta m_s$ [fs$^{-1}$ ]</td>
<td>$17.757 \pm 0.035$</td>
<td>$\pm 0.017$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
<td>$</td>
<td>$1.011 \pm 0.014$</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
<td>$0.5300 \pm 0.0016$</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
<td>^2$</td>
<td>$0.2409 \pm 0.0021$</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel</td>
<td>^2$</td>
<td>$0.0067 \pm 0.0033$</td>
</tr>
<tr>
<td>$\delta_\parallel$</td>
<td>$3.145 \pm 0.074$</td>
<td>$\pm 0.025$</td>
<td></td>
</tr>
<tr>
<td>$\delta_\perp$</td>
<td>$2.931 \pm 0.089$</td>
<td>$\pm 0.050$</td>
<td></td>
</tr>
<tr>
<td>$\delta_{S\perp}$</td>
<td>$0.48 \pm 0.15$</td>
<td>$\pm 0.05$</td>
<td></td>
</tr>
</tbody>
</table>

- $\phi_s$ and $\Delta \Gamma_s$ are found in agreement with the SM

  \[
  \phi_s^{SM} \simeq -37 \pm 1 \text{ mrad} \quad \Delta \Gamma_s^{SM} = 0.091 \pm 0.013 \text{ ps}^{-1}
  \]

- $\Gamma_s$ and $\Delta m_s$ are consistent with the latest world averages

  \[
  \Gamma_s^{WA} = 0.6573 \pm 0.0023 \text{ ps}^{-1} \quad \Delta m_s^{WA} = 17.765 \pm 0.006 \text{ fs}^{-1}
  \]

- $|\lambda|$ is consistent with no direct CPV ($|\lambda| = 1$)

- This measurement utilizes the largest ever effective statistics $N_{Bs} \cdot P_{tag}$ for a single $\phi_s$ measurement
  - The precision on $\phi_s$ is comparable with the world’s most precise single measurement by LHCb ($\phi_s = -39 \pm 22$ (stat) $\pm 6$ (syst) mrad)
  - This is the most precise single measurement of $\Delta \Gamma_s$ to date in this channel

---

Alberto Bragagnolo

CP violation at CMS

40/44
Combination with 8 TeV results

- These results supersede PLB816(2021)136188 and are further combined with those obtained CMS at 8 TeV [PLB757(2016)97], yielding

  \[ \phi_s = -74 \pm 23 \text{ [mrad]} \]
  \[ \Delta \Gamma_s = 0.0780 \pm 0.0045 \text{ [ps}^{-1}] \]

- Due to the high difference in statistical power between the two results the sensitivity gain is small

- **The combined value for the weak phase \( \phi_s \) is consistent** with the SM prediction, the latest world average, and with zero (no CPV) at 3.2 s.d.
  - This is the first evidence of CPV in \( B_s \rightarrow J/\psi K^+K^- \) decays

- These results helps to further constrain possible BSM effects in the \( B_s \) system

---

Alberto Bragagnolo

CP violation at CMS

41/44
Outlook
Summary and outlook

- This seminar presented three recent CMS results on the physics of CP violation
  - **CP violation in** $D^0 \rightarrow K_S K_S$
    - First CMS results on CP violation in the charm sector
  - **Effective lifetime measurement in the CP-odd decay** $B_s \rightarrow J/\psi K_S$
    - Most precise determination of $\tau_{\text{eff}}(B_s \rightarrow J/\psi K_S)$
  - **Measurement of the time-dependent CP violation in** $B_s \rightarrow J/\psi \phi$
    - First evidence of CP violation in $B_s \rightarrow J/\psi K^+ K^-$

- CMS recent contributions in flavor physics prove that it can be one of the leading actors in several key areas of study, such as rare decays and CP violation
- Advancements in trigger strategies and flavor tagging techniques allows CMS to compete in measurements for which the detector was not designed
- Run 3 will provide **unique** opportunities thanks of a revamped trigger strategy, which will lead to the collection of an unprecedented amount of data suitable for flavor physics studies

*Stay tuned in the future for other exciting CMS results!*
Thanks for the attention
Backup

- CP violation in $D^0$ -
Table 1: Optimized selection criteria in the signal channel $D^0 \rightarrow K_S^0 K_S^0$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ of tagging pion from $D^{*\pm} \rightarrow D\pi^\pm$</td>
<td>$&gt; 0.35$ GeV</td>
</tr>
<tr>
<td>$\eta$ of tagging pion from $D^{*\pm} \rightarrow D\pi^\pm$</td>
<td>$-1.2 &lt; \eta &lt; 1.2$</td>
</tr>
<tr>
<td>$p_T(K_S^0)$</td>
<td>$&gt; 2.2$ GeV and $&gt; 1.0$ GeV</td>
</tr>
<tr>
<td>$P_{\text{ vtx}}(D\pi^\pm)$</td>
<td>$&gt; 5%$</td>
</tr>
<tr>
<td>$P_{\text{ vtx}}(K_S^0 K_S^0)$</td>
<td>$&gt; 1%$</td>
</tr>
<tr>
<td>$P_{\text{ vtx}}(\pi^+\pi^-)$ for $K_S^0 \rightarrow \pi^+\pi^-$</td>
<td>$&gt; 1%$</td>
</tr>
<tr>
<td>$D^0$ vertex displacement from the PV in $xy$</td>
<td>$&gt; 2$ s.d.</td>
</tr>
<tr>
<td>$D^0$ vertex displacement from the PV in $xyz$</td>
<td>$&gt; 9$ s.d.</td>
</tr>
<tr>
<td>$K_S^0$ vertex displacement from the $D^0$ vertex in $xyz$</td>
<td>$&gt; 9$ s.d. and $&gt; 7$ s.d.</td>
</tr>
<tr>
<td>angle between $D^0$ momentum and displacement from PV in $xyz$</td>
<td>$&lt; 0.205$ rad</td>
</tr>
<tr>
<td>angle between $D^0$ momentum and displacement from PV in $xy$</td>
<td>$&lt; 0.237$ rad</td>
</tr>
<tr>
<td>angle between $D^0$ momentum and displacement from BX in $xy$</td>
<td>$&lt; 0.237$ rad</td>
</tr>
</tbody>
</table>
Backup
- CP violation in $B_s$ -
Penguin contributions

\[
\phi_S = \sin(2\beta) = \sin(2\beta_{\text{tree}} + \Delta\phi_{\text{penguin}}^S + \Delta\phi_{\text{NP}}^S)
\]

- Penguin pollutions are expected to be small for $B_s$, but they are not well constrained

\[
\Delta\phi_{penguin}^S \approx 3 \pm 10 \text{ mrad}
\]

- Analysis of penguin and NP contributions is possible using Cabibbo-favored control channels


B-factories CPV flagship
LHC competitive

$B^0_s \rightarrow J/\psi K_S^0$

$B^0_d \rightarrow J/\psi K_S^0$

$B^0_d \rightarrow J/\psi \pi^0$

$B^0_d \rightarrow J/\psi \rho^0$

LHC CPV flagship
B-factories not competitive

B-factories CPV flagship
LHC competitive
Offline selection

Requirements common between the two HLTs

- \(5.24 < m(\mu\mu KK) < 5.49\) GeV
- \(p_T(B_s) > 9.5\) GeV
- Vertex probability > 2%
- \(\sigma(ct) < 50\) μm
- \(|\eta(\mu)| < 2.4\)
- \(|\eta(K)| < 2.5\)
- \(|m(\mu\mu) - m(J/\psi_{PDG})| < 150\) MeV
- \(|m(KK) - m(\phi(1020)_{PDG})| < 10\) MeV

Requirements specific to the muon-tagging HLT

- \(p_T(\mu) > 3.5\) GeV
- \(p_T(K) > 1.15\) GeV
- \(ct > 60\) μm

Requirements specific to the standard HLT

- *muon-tagging* trigger vetoed
- \(p_T(\mu) > 4\) GeV
- \(p_T(K) > 0.9\) GeV
- \(p_T(\mu\mu) > 6.9\) GeV
- \(ct > 100\) μm, \(ct/\sigma(ct) > 3\)

- **Selection requirement optimized** with the a genetic algorithm to maximize \(S/\sqrt{S + B}\)
- **To avoid overlaps, the muon-tagging trigger is vetoed in the standard trigger category**
- The PV of choice is the closest in 3D to the line that passes through the SV and parallel to the \(B_s\) momentum
**OS-lepton taggers selection**

**OS Muon**

- **Requirements**
  - $p_T > 2$ GeV
  - $|\eta| < 2.4$
  - $|d_z(PV)| < 1$ cm
  - $\Delta R(B_s) > 0.4$
  - Discriminators vs fakes

- **Deployed in both trigger categories**
- **Dense DNN for $\omega_{\text{tag}}$ estimation**
  - Inputs: kinematics, IP, surrounding activity

**OS electron**

- **Requirements**
  - No OS muon selected in the event
  - $p_T > 2.5$ GeV
  - $|\eta| < 2.4$
  - $|d_z(PV)| < 0.2$ cm
  - $|d_{xy}(PV)| < 0.08$ cm
  - $\Delta R(B_s) > 0.4$
  - Discriminators vs fakes

- **Deployed only in the standard trigger category**
- **Dense DNN for $\omega_{\text{tag}}$ estimation**
  - Inputs: kinematics, IP, surrounding activity

Alberto Bragagnolo  
CP violation at CMS
Taggers combination

- **Overlap logic**

<table>
<thead>
<tr>
<th></th>
<th>OS muon</th>
<th>OS electron</th>
<th>OS jet</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS muon</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>OS electron</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>OS jet</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>SS</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

- **Tag decision combination**

\[
\zeta(\xi_1, \xi_2, \omega_1, \omega_2) = \begin{cases} 
\zeta_1 & \text{if} \quad \omega_1 < \omega_2 \\
\zeta_2 & \text{if} \quad \omega_2 < \omega_1 
\end{cases}
\]

- **Mistag combination**

\[
p(b) = \prod_{i=1}^{2} \left( \frac{1 - \xi_i}{2} + \xi_i (1 - \omega_i) \right) \quad p(\bar{b}) = \prod_{i=1}^{2} \left( \frac{1 + \xi_i}{2} - \xi_i (1 - \omega_i) \right)
\]

\[
P(\bar{b}) = \frac{p(\bar{b})}{p(\bar{b}) + p(b)} \quad P(b) = \frac{p(b)}{p(\bar{b}) + p(b)}
\]
Mixing asymmetry for different tagging categories

All categories are mutually exclusive

All, but the first, refers to the standard trigger category

Alberto Bragagnolo  
CP violation at CMS
Fit projections \textit{(standard trigger category 2018)}
Systematic uncertainty classification

- **Type-I: unaccounted uncertainties**
  - Account for the finite statistics of simulated/control samples and uncertainties in calibrations and efficiency
  - **Always** propagated to the final results
  - Evaluated with two procedures
    1. **Type-I full**: obtained by sampling the samples/parameters of interest ~100 times, repeating the fit each time, and taking the RMS of the results as uncertainty
    2. **Type-I simple**: obtained by sampling a parameter only two times at $\pm 1\sigma_{\text{stat}}$

- **Type-II: method and model assumptions**
  - Account for possible bias induced by the assumptions made in the fit model and the analysis methods
  - Evaluated only if a significant bias is observed while testing an alternative (good) hypothesis
  - A significant bias for a parameter $V$ is defined as a difference $\Delta$ in the fit results of more than 20% of its $\sigma_{\text{stat}}$
  - In these cases, **half of the bias** is taken as uncertainty, assuming that the true bias is uniformly distributed between 0 and $\Delta$

The fit bias does not fall into either of these two categories
## Comparison with theory and world averages

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured value</th>
<th>World-average value</th>
<th>Theory prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ [mrad]</td>
<td>$-73 \pm 24$</td>
<td>$-49 \pm 19$</td>
<td>$-37 \pm 1$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>$0.0761 \pm 0.0047$</td>
<td>$0.084 \pm 0.005$</td>
<td>$0.091 \pm 0.013$</td>
</tr>
<tr>
<td>$\Gamma_s$ [ps$^{-1}$]</td>
<td>$0.6613 \pm 0.0032$</td>
<td>$0.6573 \pm 0.0023$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\Delta m_s$ [ps$^{-1}$]</td>
<td>$17.757 \pm 0.039$</td>
<td>$17.765 \pm 0.006$</td>
<td>$18.77 \pm 0.86$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
<td>$</td>
<td>$1.011 \pm 0.018$</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
<td>$0.5300 \pm 0.0047$</td>
</tr>
<tr>
<td>$</td>
<td>A_{\perp}</td>
<td>^2$</td>
<td>$0.2409 \pm 0.0037$</td>
</tr>
<tr>
<td>$</td>
<td>A_S</td>
<td>^2$</td>
<td>$0.0067 \pm 0.0034$</td>
</tr>
<tr>
<td>$\delta</td>
<td></td>
<td>$</td>
<td>$3.145 \pm 0.078$</td>
</tr>
<tr>
<td>$\delta_{\perp}$</td>
<td>$2.931 \pm 0.102$</td>
<td>$3.08 \pm 0.12$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\delta_{S\perp}$</td>
<td>$0.48 \pm 0.16$</td>
<td>$0.23 \pm 0.05$</td>
<td>$-$</td>
</tr>
</tbody>
</table>
Flavor tagging in Phase-2 with MTD

- The MTD (Mip Timing Detector) provides time information of charged tracks at its surface.
- The reconstruction algorithm utilizes compatible times of tracks from a vertex to offer time-of-flight based particle identification (PID) as a natural byproduct.
- Same-side tagging could utilize charge correlation between the s-quark in the $B_s$ and a nearby soft kaon for flavor tagging.
- The PID from MTD, when integrated in the Phase-2 extrapolation of this analysis, shows a significant improvement of the tagging performances.

![Simulated PID efficiencies](image)

<table>
<thead>
<tr>
<th>PID scenario</th>
<th>Gains in $P_{\text{tag}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC truth (perfect PID &lt; 3 GeV)</td>
<td>+66%</td>
</tr>
<tr>
<td>PID with $\sigma_{\text{BTL}} = 40$ ps</td>
<td>+24%</td>
</tr>
<tr>
<td>PID with $\sigma_{\text{BTL}} = 70$ ps</td>
<td>+14%</td>
</tr>
</tbody>
</table>